the operator biological traumas in these operative conditions and so the criteria of the aforesaid standards were not performed. On the other hand, a continuous rolling of the tractor occurred in the simulation performed by positioning the tractor on the plane with the calculated slope. Therefore, three planes with different slopes were supposed to compose the soil to give non-continuous rolling of the tractor. At the beginning of the simulated dynamics, the tractor was positioned on the plane with a slope of 40°, in such a way that the resultant weight force was able to make the tractor roll over. The intermediate plane with a slope of 20° was actually the one that the rolling over tractor finally hits. The third plane was horizontal (Figure 2).

At first an isotropic elastic, perfectly plastic constitutive model was used (Peruzzi and Sartori, 1997). Subsequently, the simulation model was improved by considering two types of terrains with quite different mechanical properties: i) a sand-based soil; and ii) a clay-based soil. The parameter values used in the accident model are reported in Table 1 (Lancellotta, 1987).

The tractor operator - dummy

The numerical dummies allow simulation of the dynamic behaviour of the real instrumented dummies commonly used in the crash tests for road vehicles (TNO, 2010). As is well known, dummies have suitable joints calibrated on the basis of knowledge obtained in the field of biomechanics through tests on volunteers and dead bodies (Schmitt *et al*., 2014). The dummy numerical models are then multibody systems with kinematics joints and restraints, which reproduce the connections present in the instrumented dummies usually used in the crash tests. The Hybrid III 50th percentile male dummy, representing the size and weight of an *average* adult male, simulated the tractor operator in the rollover scenario (TNO, 2010). In the technical standard (European Commission, 1987; OECD, 2014) the position of the driver on the narrow track tractor is considered as prone on the steering wheel. In this study, the chosen dummy, defined by a single multi-body system, was positioned on the tractor seat with its arms holding the wheel (Figure 1C and D).

Results and discussion

The roll-over kinematics

The analysis of the kinematic parameters concerning the simulation of the tractor overturning does not highlight appreciable differences between the case of the belted dummy and the case of the unrestrained dummy, probably because the dummy mass compared with that of the whole tractor is negligible. Therefore the obtained kinematic results are reported only with reference to the belted dummy. Some kinematic quantities of main interest concerning: i) clay; ii) sand; and iii) rigid soils considered have been represented as functions of time in Figures 3 and 4, *i.e.*, the longitudinal (x-) component of the tractor body angular velocity and acceleration. The rapid variation of the components of the velocity and acceleration at the instant of time $t^* \approx 1130$ ms from the beginning of the simulation highlights the main shock to the system when hit the soil on its side (Figure 2).

As expected, the tractor bounced on the rigid soil with a series of fol-

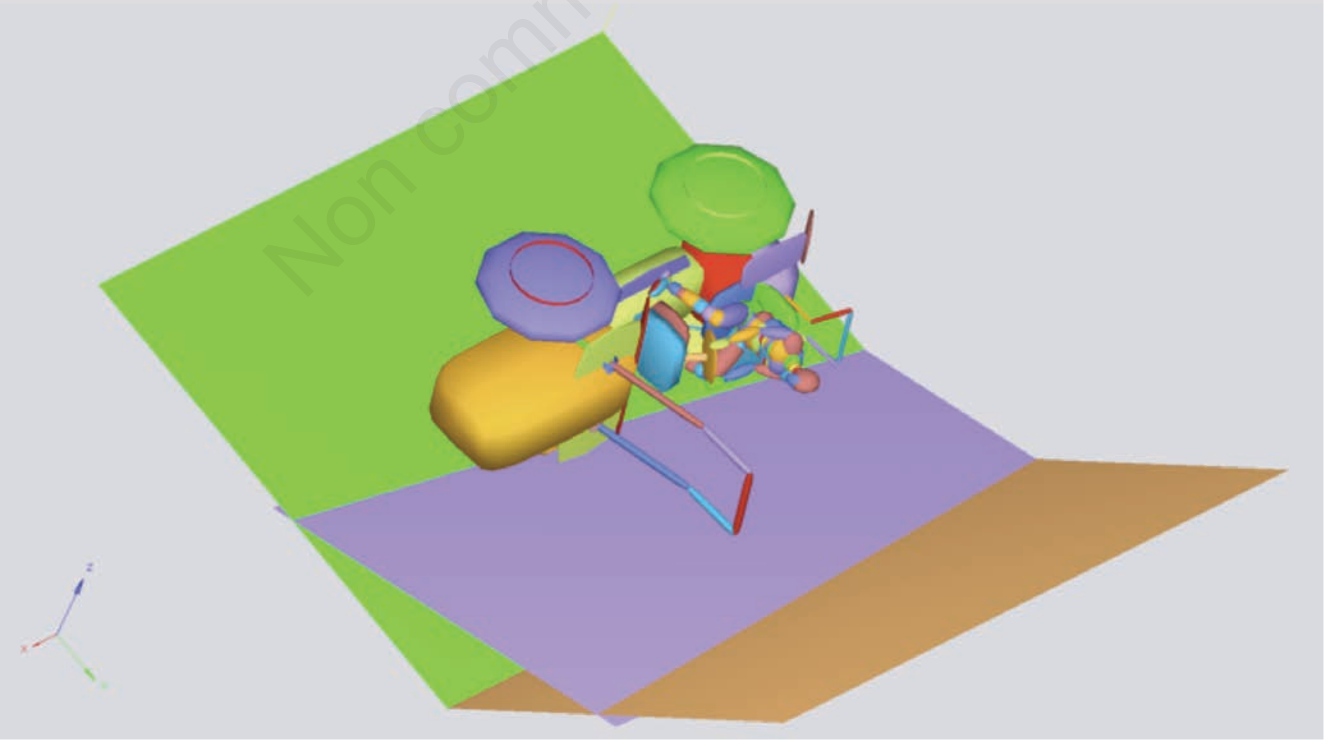

Figure 2. The instant of time in which the main shock occurs (1130 ms).

lowing shocks, each of which contained a step variation of the angular velocity vector (Figure 3) and an extremely high peak value of the angular acceleration (Figure 4). Similar considerations can be made referring to velocity and acceleration of the tractor body centre of gravity, which on average moved down along the slope. It is useful to underline that the body surfaces are supposed to have a hyper-ellipsoidal form, therefore the contact region between the parts of the system and the soil was in each case reduced to a single contact point as the body stiffness approached infinity. This behaviour is actually far from the real situation. Furthermore also the two frames were considered infinitely rigid and this is clearly a non-real situation.

On the other hand, in the cases of sandy and clayey soil all the acceleration peaks reduce to realistic values and, in particular, the time interval during which the first main rebound of the tractor body becomes longer. In conclusion, a slower variation of the kinematic quantities was obtained, with a consequently more realistic representation of the rollover dynamics of the tractor.

The final time of the simulations is shown in Figure 5. The plastic deformations of the soil related to the interaction with the tractor body and mainly with the front safety frame can be clearly seen.

The biological traumas occuring to the operator

In the case of rigid soil, comparison of the values concerning the considered injury parameters regarding the operator restrained with a 2-point pelvic restraint and the non-restrained operator highlights that the biological damage in the absence of a restraining system are severe, as expected (Figure 6). The analysis of head injuries is linked to accelerations that this part of the body suffered during the simulation. The unrestrained driver was thrown from the seat and impacted with the soil; the head came into contact with the soil after 1328 ms and the contact force reached its maximum value at 1330 ms. The results emphasized an *HIC* value of 1465.4 (Figure 6), in the time range corresponding to highest resultant acceleration, that was between t_1 = 1327.3 ms and t_2 = 1331.1 ms. The restrained driver was not thrown from the tractor, and remained inside the safety volume maintained by the ROPS. However, the head suffered acceleration variations, even if the maximum value of the acceleration vector was 217.5 m s^{-2} (t = 1226 ms) corresponding to 22.2 g, which is far below the threshold value, and the *HIC* value was equal to 124.65 in correspondence with the time interval with extreme t_1 = 1223.5 ms and t_2 = 1259.5 ms (Figure 6). Therefore, in this case the risks of serious or

Table 1. Mechanical property parameters of the two considered soils.

Soil	Mass density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Yield stress (kPa)
Sand	1600	200	0.3	200
Clay	1800	40	0.3	120

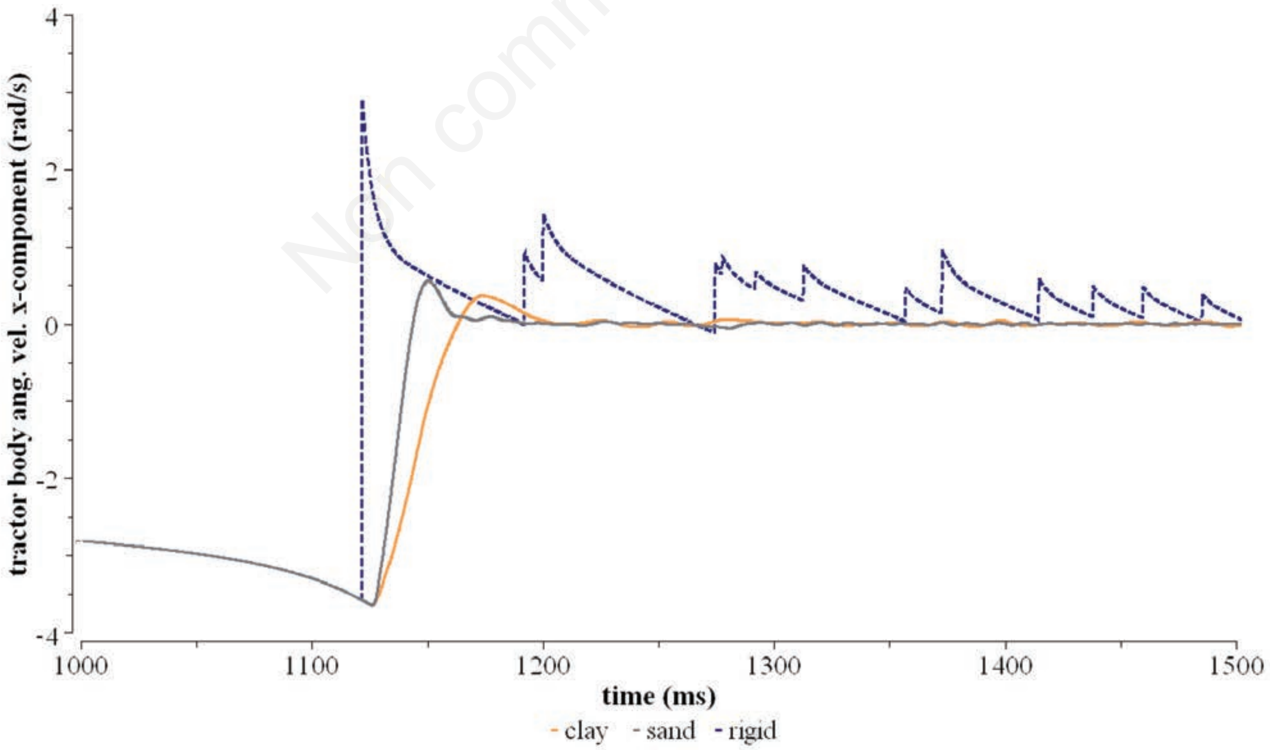

Figure 3. The x-component of the tractor body angular velocity as function of time.

fatal injury were minimal. The neck injury predictor regarding tension and extension loading (N_{TE}) exceeded the corresponding threshold value only for the unrestrained driver. Due to its impact with the soil the head rotated rearwards and tensile force and an extension moment were applied on the neck. Tension-extension loading commonly occurs when unbelted occupants hit the windscreen or when the chin impacts on the dashboard (Schmitt *et al*., 2014). On the other hand, the compression-flexion loading (N_{CF}), which may result from a frontal impact in which the torso is restrained and the neck is meant to stop head movement, did not exceed the limit value for both the considered drivers. The non-restrained operator's thorax centre of mass underwent an acceleration of 718.92 m s^{-2}, corresponding to 73.3 g following the crash with the soil. This value was then beyond the threshold value for *3ms*, while the acceleration suffered by the restrained driver was clearly far below this limit. Furthermore, the non-restrained operator's collision with soil affected the tibia because the limit value for *TI* was exceeded; there were no consequences for the femur because *FFC* threshold was not exceeded. Finally, the possibility offered by the pelvic belt of confining the operator within its safety volume greatly reduced all injuries, as was also expected. In this case, the criteria threshold was exceeded only for the tibias, but less than in the case of a non-restrained operator. A side-bag with an opportune counter-reacting structure could be used in order to completely avoid this kind of injury. The values of several injury parameters in the case of operator restrained with a 2-point pelvic belt are reported in Figure 7, where the results from the simulated tractor-soil impact obtained considering real stiffness values and the constitutive material model of the clay- and sand-based soils are compared with those obtained in the case of rigid soil. None of the injury parameters exceeded the corresponding threshold value and this aspect has highlighted the usefulness of the seat belt, as expected. Furthermore, driver injury increased as the stiffness of the soil decreases as seen from comparison of the biological damage values obtained with the different soil simulations: the injuries assessed with a clayey soil were greater than those obtained with a sandy soil, which were greater than those obtained with a rigid soil. The distinct stiffness values clearly influenced the extent to which the ROPS penetrated into the soil and so soil deformation also affected the safety volume, which diminished as the stiffness of the soil lessened. In conclusion, the increased deformation of the soil caused a more probable interplay between the tractor driver and the soil.

Conclusions

The multibody techniques currently utilized in the automotive sector could also be used for agricultural accidents, and this paper reports an example in which this approach is used to evaluate the severity of the injuries to the driver associated with the rollover of an agricultural tractor. According to the obtained results, the seat belt plays an important role in confining the operator inside the safety volume of the tractor so that all injuries are reduced. In the simulated accident, the use of the 2-point pelvic restraint prevented the operator from being thrown out of the tractor and impacting with the soil, thus preventing damage to the head and neck. Soil deformation produced lower acceleration and velocity values than those obtained considering a rigid soil. Furthermore, the obtained results have shown that the higher the soil's plastic deformations the greater was the penetration of the ROPS into the soil, thereby reducing the safety volume and increasing the possibility of interactions between the operator and the soil. It should also be noted that with the roll-bars shaped as rigid bodies, the acceleration of the head and the stresses discharged on the neck at the time of contact between them and the soil were definitely more than the real stresses that would have occurred if the two roll-bars had been modelled as deformable bodies. The real ROPS are far from being perfectly rigid in these accidents and extensive plastic deformation of ROPS

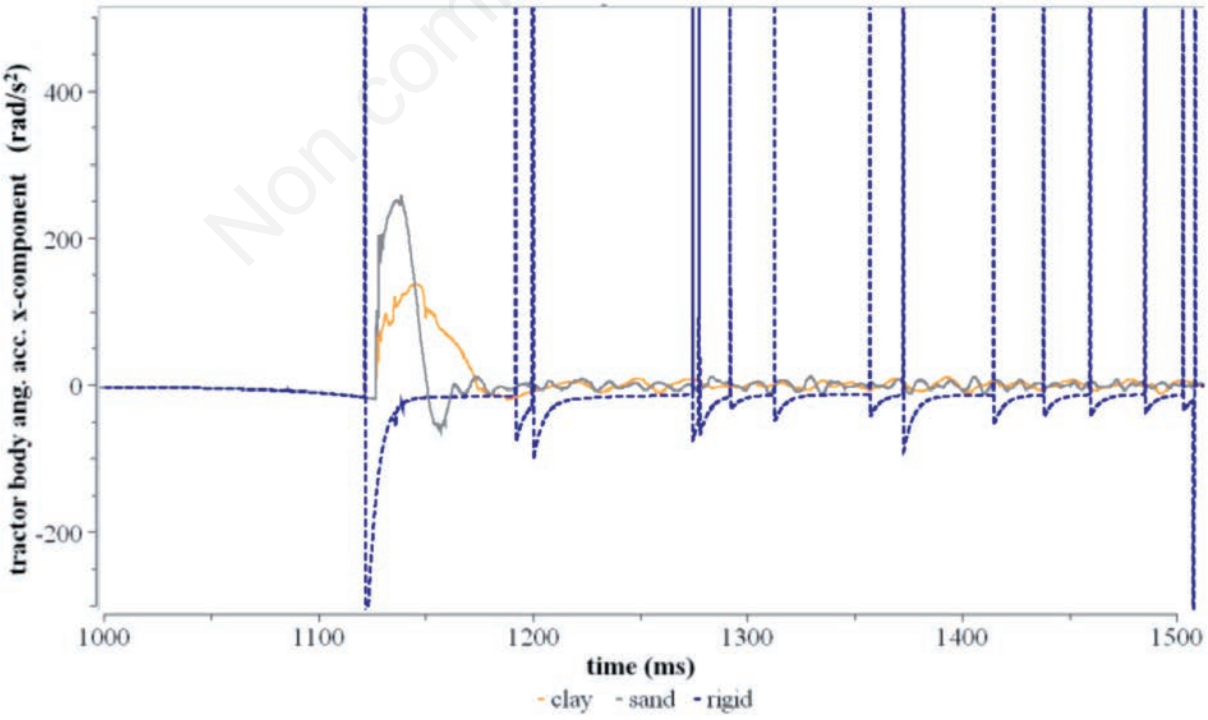

Figure 4. The x-component of the tractor body angular acceleration as function of time.

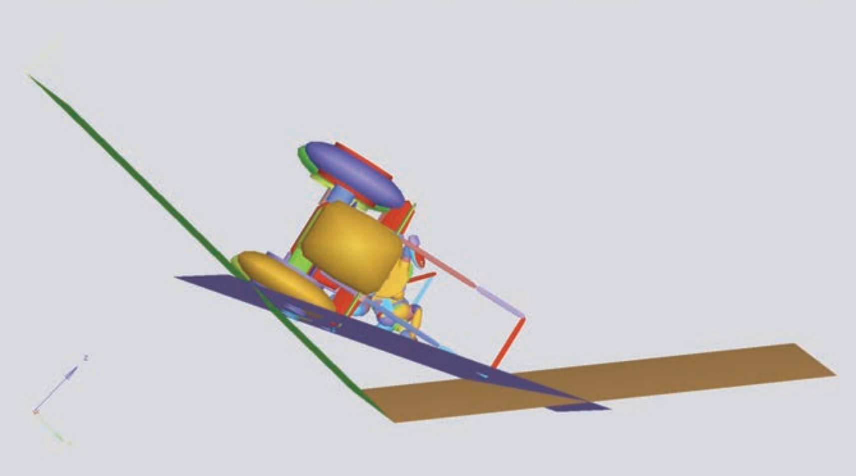

Figure 5. End of the simulation: it is possible to visualise the contacts between the dummy-tractor system and the soil.

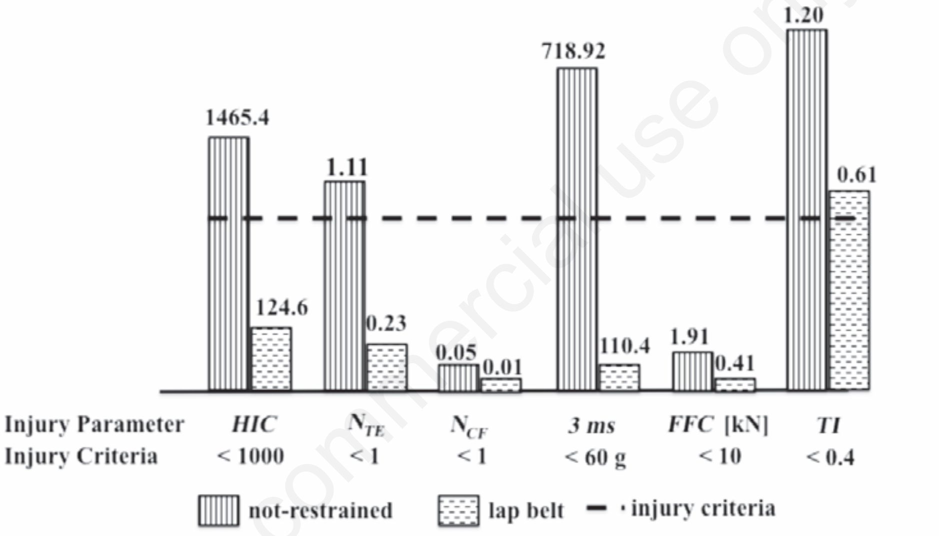

Figure 6. Comparison of the main injury parameters in the cases of: i) non-restrained dummy; and ii) dummy restrained by a 2-point pelvic belt. *HIC*, head injury criterion; N_{TE}, neck injury predictor for tension and extension; N_{CF}, neck injury predictor for compression and flexion; *3ms*, criterion for thorax injury; *FFC*, femur force criterion; *TI*, tibia index.

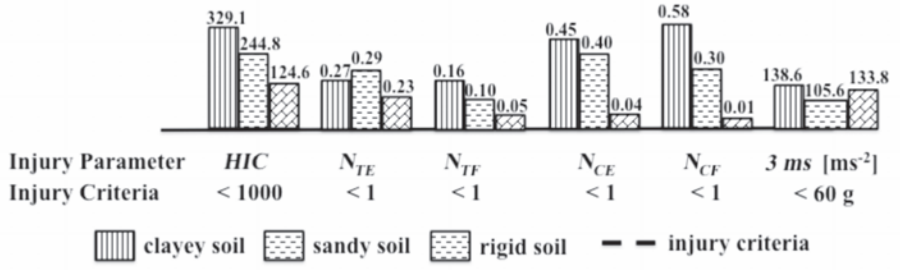

Figure 7. Comparison of the main injury parameters in the case of operator restrained with a 2-point pelvic belt considering each one of the examined soils. *HIC*, head injury criterion; N_{TE}, neck injury predictor for tension and extension; N_{TF}, neck injury predictor for tension and flexion; N_{CE}, neck injury predictor for compression and tension; N_{CF}, neck injury predictor for compression and flexion; *3ms*, criterion for thorax injury.

structures during rolling absorbs energy, lowering acceleration peaks.

Therefore, further improvement of the simulation model will take account of the deformability of the safety ROPS and a more accurate model of the agricultural soil, and will be dealt with in a study of the FEM problem. Furthermore, in addition to the finite element analysis of the arches of protection, with which to get an overview of their most truthful stresses and deformations, the deformation of the structures through appropriate discretization of the model in rigid bodies connected by junctions of various type, able to develop actions that reproduce the characteristics of resistance of the elements deformed, will be pointed out. An example of this approach might consider a plastic hinge in the attachments between strings and casing, such as to shape the plastic deformation.

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